

APPENDIX E

ENPEP: AN INTEGRATED APPROACH FOR MODELING ENERGY SYSTEMS

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INTRODUCTION

The **EN**ergy and **P**ower **E**valuation **P**rogram (ENPEP) is a set of microcomputer-based analytical tools for conducting integrated energy and environmental planning. ENPEP consists of nine technical modules, each having automated connections to other ENPEP modules but also having stand alone capability. A typical ENPEP study would likely involve more than one module but would not utilize all nine modules. The technical modules and their primary functions are:

MACRO	Allows the user to specify macroeconomic growth (global or sectoral) that will be the drivers of energy demand.
DEMAND	Projects energy demand based upon the macroeconomic growth information provided in MACRO.
PLANTDATA	Provides, for use in other modules, a library of technical data on electric generating plants.
BALANCE	Computes equilibrium energy supply/demand balances over the study period.
MAED	Portrays the electrical demand as part of overall energy demand.
LDC	Characterizes the electrical load over time for use in other modules.
ELECTRIC	The microcomputer version of WASP-III, determines the minimum cost expansion plan for the electrical generating system.
ICARUS	Performs detailed production cost and reliability calculations for a specified electrical generating system.
IMPACTS	Estimates environmental residuals and resource requirements for the energy system determined by BALANCE and/or ELECTRIC.

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ENPEP provides the potential for energy planners in industrialized or developing countries to carry out timely studies without access to inconvenient and/or expensive mainframe computers. The ENPEP package provides a comprehensive energy/economic/environmental framework needed for analysis and decision-making. Numerous applications are underway. Enhancements and upgrades are performed on a continuing basis. Original support for the package was provided by the U.S. Department of Energy. Additional assistance in enhancements and applications has been received from the International Atomic Energy Agency, the World Bank, and the Hungarian Electricity Board.

THE ENPEP APPROACH

There were several considerations that went into the design of ENPEP. First, it was determined that ENPEP should be a comprehensive package that allowed the energy analyst to carry out complete energy system studies. To the extent possible, ENPEP was to be an all-purpose tool that would provide the user with most of what was needed to do a complete energy analysis. It was recognized that this was a noble goal but that no single model or set of models could ever provide all that was needed for energy planning. Nevertheless, ENPEP was to be designed to accomplish as much of this as possible.

In attempting to meet this requirement, ENPEP was planned as a modular but integrated package. It was to be modular in that it would consist of a series of energy planning models, each of which would address a portion of the energy planning need. These modules were to be useful either as a stand-alone package or as an integral part of the rest of the ENPEP system. ENPEP was to be integrated in that each of these modules was to be able to generate data and information that was useable by other modules and that could be passed to the other modules without the user having to reenter the information. This integration of the files and information would make operation of ENPEP more efficient for the user.

The modular structure would also allow for an evolution of ENPEP as new and improved techniques became available. ENPEP was envisioned as a package that would undergo continual improvement and enhancement. Individual modules could be upgraded and replaced as time and resources permitted.

The second major requirement for ENPEP was that it was to be microcomputer-based. Experience in developing countries and in planning agencies in some developed countries had shown that access to mainframe computers was limited and that having a planning tool operational on a microcomputer would greatly enhance the utility of the system to the energy analyst.

At the time the ENPEP development was begun the most advanced of the microcomputers suitable for this type of application was the IBM AT-class machine. This used the Intel 80286 chip as the basis of its architecture. While technology developments have rendered this type of system as "entry-level" rather than "state-of-the-art", it still remains as the most advanced machine available in many countries. ENPEP's evolving design takes advantage of the more advanced systems while maintaining the ability of the analyst to use it on the earlier versions of microcomputer equipment.

The third major requirement for ENPEP was that the theoretical basis for its analytical approach be well-recognized and accepted in the energy analysis community. If the package were to see widespread use, it must use demonstrated planning techniques that were useful in providing decision-making information. From its inception, ENPEP was structured to incorporate approaches that were theoretically sound and defensible.

It was with these basic design considerations that ENPEP was constructed. It was first released in 1986 and has seen several major updates since then.

THE ENPEP STRUCTURE

Overall Structure

Figure E-1 gives the overall structure of the ENPEP model. There are several pathways that a user may take through ENPEP. Each of the modules can be used independently or in conjunction with other modules as shown on the figure. The MACRO module is the portion of ENPEP that deals with macroeconomic growth projections. While MACRO is not an economic planning model, it does provide for an interface with any economic planning model and/or results the energy analyst has access to. The DEMAND module translates the macroeconomic projections from MACRO into energy demand projections. In DEMAND the user is given the choice of projecting fuel and electricity demand directly or using the more rigorous useful energy demand approach.

The BALANCE module is used to construct the supply/demand balance for the entire energy system. It is one of the main modules in ENPEP. It uses a non-linear, generalized equilibrium approach in carrying out these calculations. The theoretical approach of BALANCE has been used in many energy analyses.

The IMPACTS module computes the impacts of the energy supply and demand system that has been developed from BALANCE. It addresses air pollution, water pollution and water supply, land use, solid waste generation, human and material resource requirements, and occupational health and safety. IMPACTS allows for the analysis of different regulatory approaches to controlling these impacts.

For users seeking to do a more detailed analysis of the electric system portion of the energy sector, ENPEP provides a specialized series of modules. The PLANTDATA module allows for the input of electric system generating unit data in a consistent fashion for evaluation. PLANTDATA information can also be used as input to BALANCE.

The LDC module generates detailed load duration curves for use in electric system planning. The basic annual load forecasts may come from BALANCE, MAED, or from direct user input.

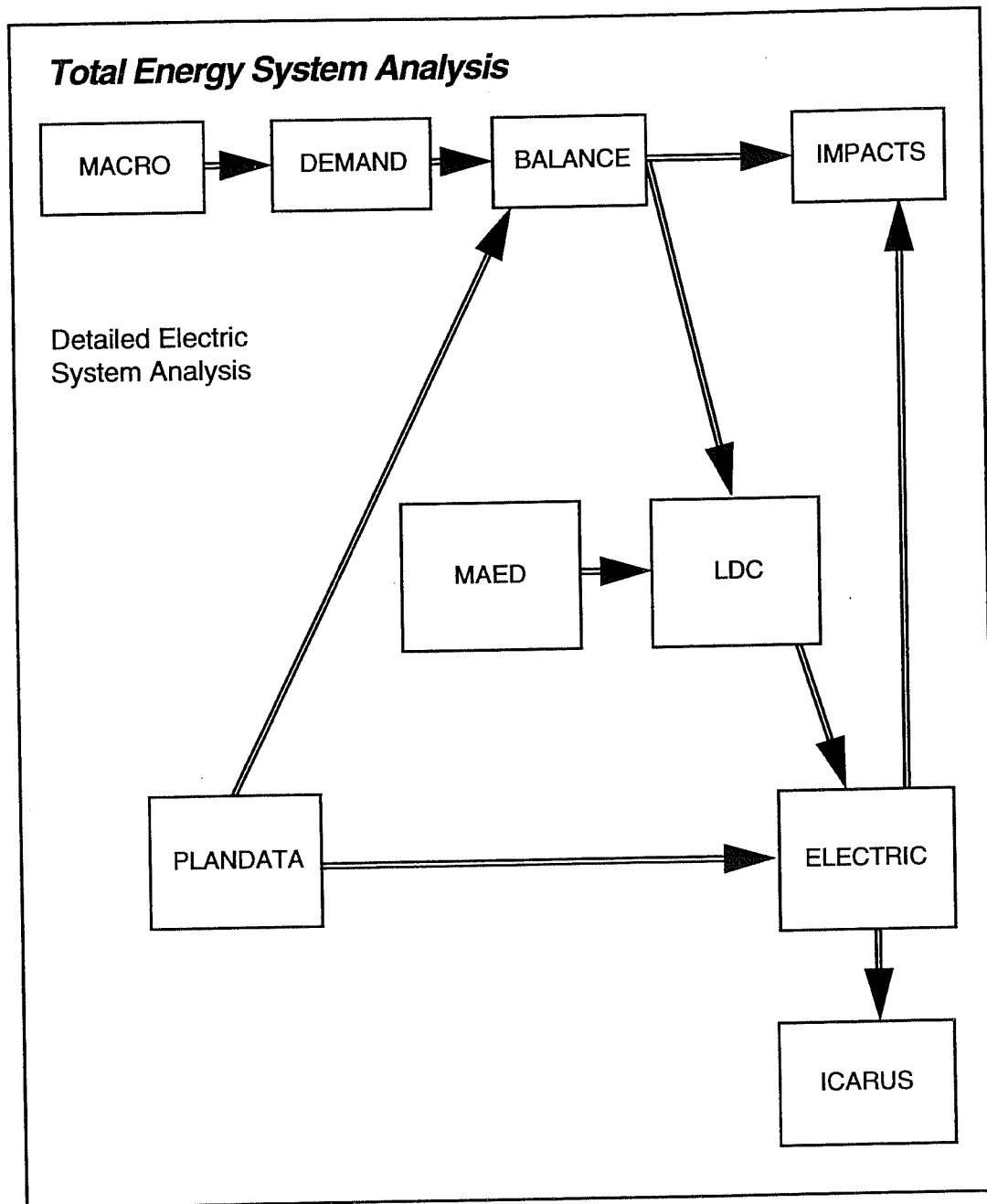


Figure E.1 ENPEP Structure

The ELECTRIC module is another key component of ENPEP. It is an electric system expansion planning model that is based on the WASP-III model distributed by the IAEA. It uses a cost-optimization technique to develop a build schedule for the electric system. The mainframe version of ELECTRIC (WASP-III) is probably the most widely used energy planning tool in the developing world.

The ICARUS module is designed to give a detailed analysis of electric system production cost and reliability. It uses a build schedule derived from ELECTRIC or other expansion planning analysis.

The MAED module provides the user with an alternative method of developing an annual electric load forecast. While MAED provides some information on non-electric energy use, this is only in a very aggregated form. MAED output can also be fed into the LDC module.

The output of the ELECTRIC module can be run through the IMPACTS module to determine the impacts of the electric sector. This can be done either alone or in conjunction with the output of the BALANCE module.

The computer architecture of ENPEP is designed for modularity and user-friendliness. A forms package provides data entry screens and menus for selecting operations. Files are set up for access among the various modules of ENPEP to minimize redundant keying of data. Each module of ENPEP is set up for operation independently or in connection with other modules.

More detailed descriptions of each of the modules and the computer architecture of ENPEP is given in the following sections.

3.2 MACRO

The MACRO module is designed as the interface between ENPEP and other economic analysis tools. MACRO itself is not an economic planning model. Rather, it allows the user to format the results of economic studies into a structure that can be used by the other modules in ENPEP. The MACRO module performs five main functions:

- Defines the planning period
- Processes currency conversions
- Processes GDP growth projections
- Processes population growth projections
- Processes special parameter growth projections

In the output reports, MACRO provides both tabular and graphical displays of the GDP, population, and special growth by sector, subsector, or intermediate aggregations. Each of the parameters entered into MACRO is given a unique identifying code. This allows the user to apply the growth in that parameter to some portion of the energy demand in the DEMAND module.

3.3 DEMAND

The DEMAND module is designed to generate projections of energy demand that are tied to the growth rates (GNP, population, or special) input into the MACRO module. By allowing for an explicit link to economic and other variables, DEMAND allows the user to see how these parameters might affect energy use. Numerous variations can be tested to evaluate the effect of changes in the parameters on energy demand. In carrying out its analysis, DEMAND performs four basic functions:

- Defines energy units
- Processes base year energy consumption
- Processes base year useful energy demand (optional)
- Computes projected energy demand

The user is given a set of reports that cover the energy units that have been defined, the base year energy consumption by fuel type and sector, and the projected energy consumption (and/or useful energy demand) by sector. DEMAND also prepares a set of files that transmit demand growth rates for subsequent use in the BALANCE module.

3.4 BALANCE

The central requirement of a comprehensive energy analysis is the evaluation of alternative configurations of the energy system that will balance energy supply and demand. The BALANCE module is designed to provide the planner with this capability.

BALANCE uses a non-linear, equilibrium approach to determining the energy supply demand balance. In this formulation, an energy network is designed that traces the flow of energy from primary resource (e.g., crude oil, coal) through to final useful energy demand (e.g., residential hot water, industrial steam). Demand is sensitive to the prices of alternatives. Supply price is sensitive to the quantity demanded. BALANCE seeks to find the intersection of the supply and demand curve. In its operation, BALANCE simultaneously finds the intersection for all energy supply forms and all energy uses that are included in the network.

There are two major operations in BALANCE:

- Definition of the energy network
- Development of the equilibrium solution

Definition of the Energy Network BALANCE uses a set of submodels, called *nodes*, to represent different components of the energy system. Table E-1 gives the nodes available to BALANCE and the symbol used for each. The user connects these nodes by a set of *links*. The links convey two pieces of information from one node to another: price and quantity. Figures E-2 and E-3 give examples of how a supply system portion and a demand sector of the network, respectively, can be represented with nodes and links. All sectors of the energy supply and demand system are included in a BALANCE analysis. Figure E-4 shows the sectors that might be represented. The user

is free to define the sectors and the nodes and links that are in each sector to meet specific analysis needs.

Before proceeding to a discussion of how the equilibrium solution is developed, a brief description of each of the nodes and the relevant computational equations is presented.

Depletable Resource Node This node is designed to simulate the use of a depletable resource such as crude oil, coal, or natural gas. There is no input link to this node as this represents the starting point of the energy supply system. The output link carries the quantity of the resource produced (e.g., crude oil production) and its production cost.

In simulating the production cost of a depletable resource, account is taken of the fact that the marginal cost of producing the next unit of the resource will increase as the resource is used up. A simple quadratic is used to describe this behavior as shown in Equation E-1:

$$P_t = A(Q) \times (1 + R_t) + B(Q) \times Q_t + C \times Q_t^2 \quad (\text{E-1})$$

where:

- P_t is the production cost of the resource in period t
- $A(Q)$ is the intercept of the supply curve
- R_t is the growth rate in real terms of the cost of the resource
- B is the slope of the supply curve
- C is a quadratic coefficient for the supply curve

The coefficients A , B , C are user-defined and are based on an evaluation of the historical performance of the resource production. Figure E-5 shows the shape of the curve and the relationship of the coefficients.

Table E-1 Nodes Available in the BALANCE Module

SYMBOL	NODE	USE
	Depletable Resource	Simulates depletable resources such as crude oil, coal, natural gas.
	Renewable Resource	Simulates renewable resources such as solar, biomass.
	Conversion	Simulates technologies that convert one form of energy to another (e.g., electric power stations)
	Multiple Output	Simulates technologies that produce two or more forms of output energy for one form of input energy (e.g., refineries, cogenerators)
	Multiple Input	Simulates technologies that require two types of energy input to produce one form of energy output (e.g., solar water heater with electric backup)
	Decision	Simulates market decisions that chose among energy alternatives.
	Pricing	Simulates pricing policies that change the price but not the quantity of an energy form.
	Stockpiling	Simulates the stockpiling of excess production.
	Electricity Dispatching	Simulates the dispatching of electrical generators according to the load duration.
	Demand	Simulates the final demand for energy or energy services.

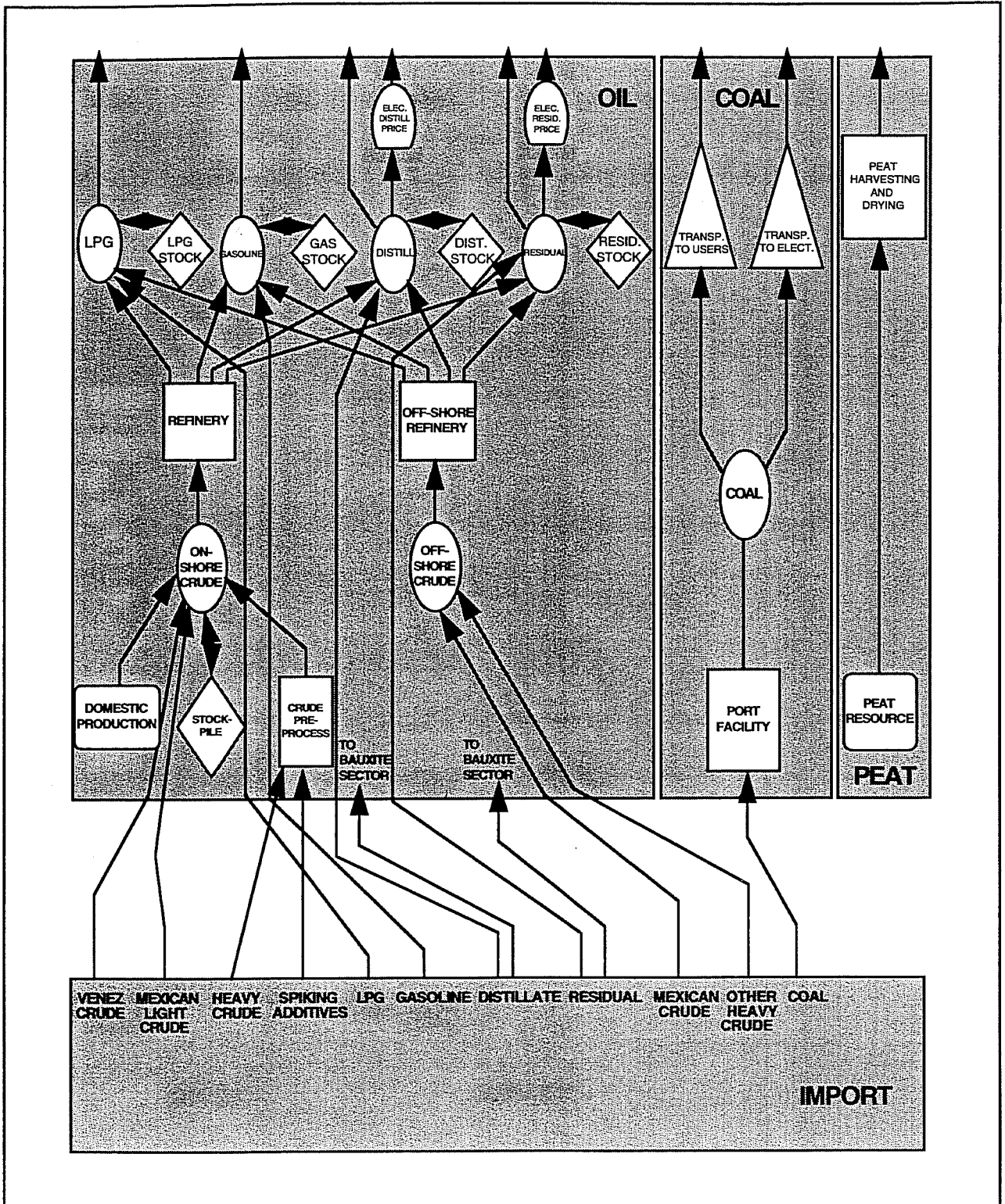


Figure E.2 Typical Supply Sector Network in BALANCE

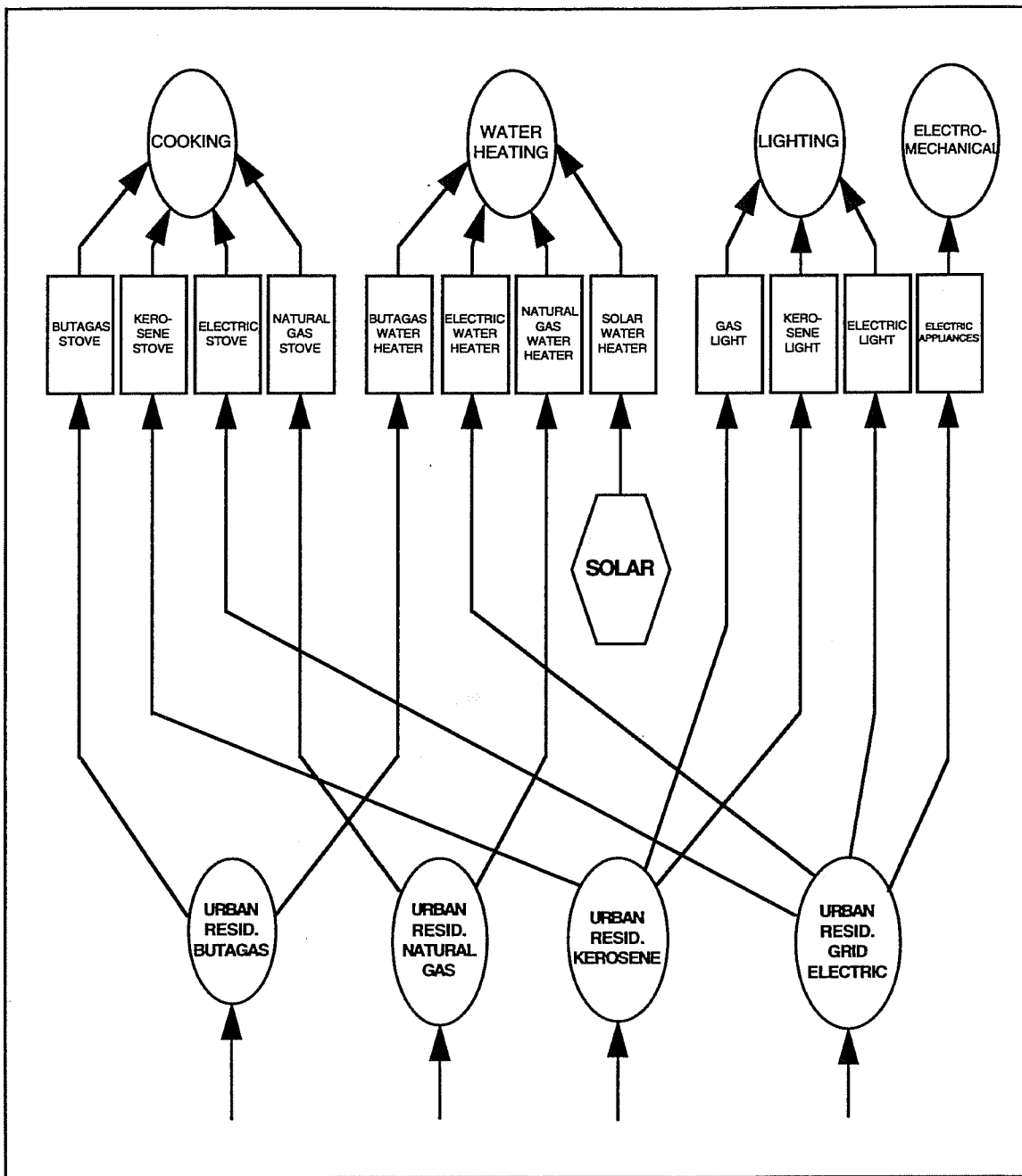


Figure E.3 Typical Demand Sector Network in BALANCE

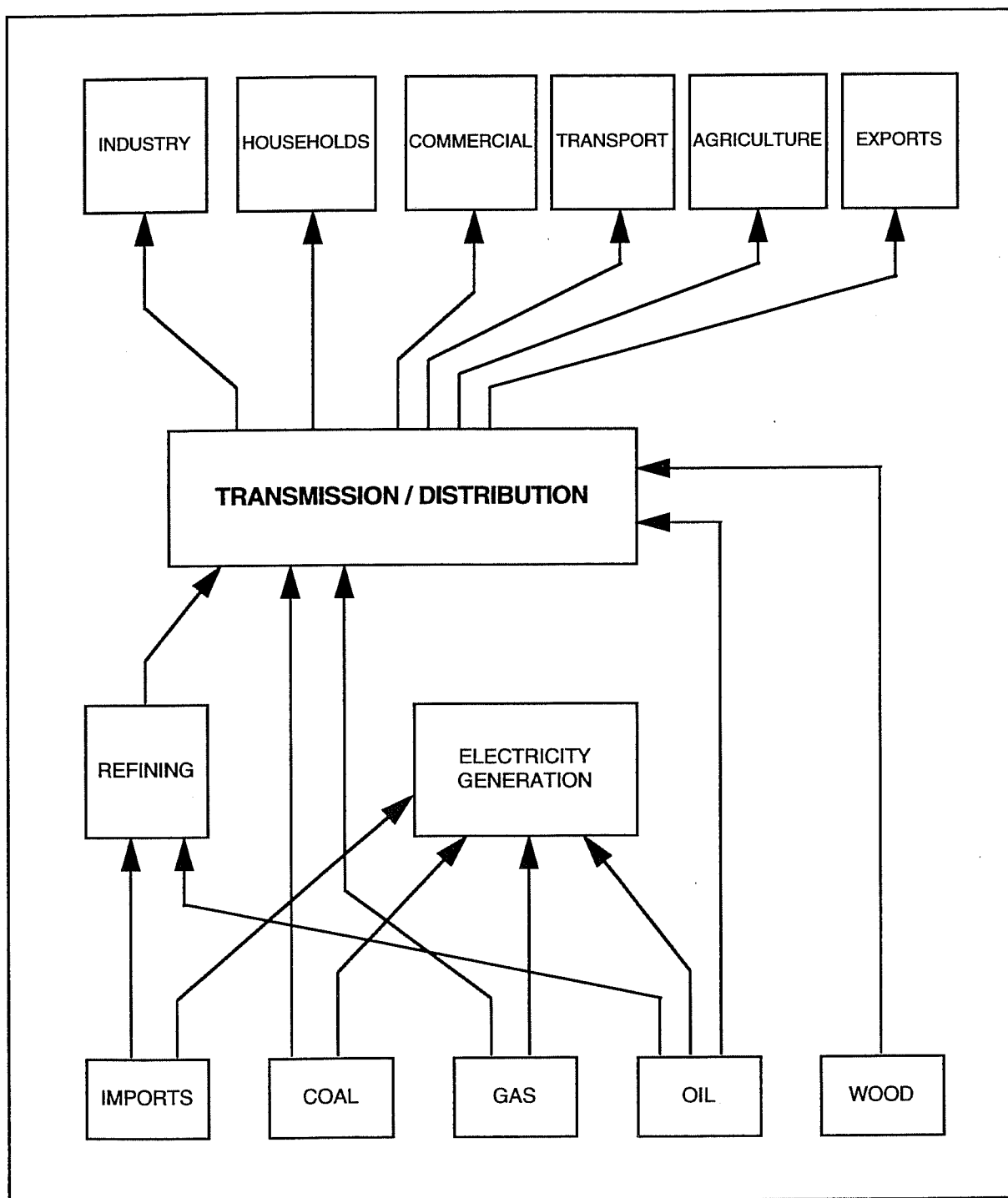


Figure E.4 Typical Sectors Included in BALANCE

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A set of supply curves is used for all of the depletable resources included in the analysis. These may be at an aggregate level (e.g., one supply curve for all domestic crude oil production) or may be a detailed level (e.g., a separate supply curve for each oil field).

The supply curves provide the cost of production that is used in the equilibrium calculation. The intersection point must be found for all sources of supply simultaneously.

Depletable resources generally have associated with them an "economic rent" that is the difference between the production cost and its selling price. The economic rent can either be included in the supply curve (by adjusting the coefficients A, B, C to represent price rather than cost) or by using the pricing node, which is described later.

The depletable resource node is also used to simulate the import of energy. In this case the coefficients B and C are normally set to zero. The projected price of imported fuels is then determined by the first term of the equation.

Renewable Resource Node This node is analogous to the depletable resource node in that it conveys production cost and quantity information. However, the production cost is simulated using a step function rather than a quadratic. This is illustrated in Figure E-6.

The approach for renewable resources is based on the premise that a renewable resource, if produced at a rate that is within the bounds of the sustainable yield, would have a constant production cost. Higher costs are incurred if production is increased to the point that less economic sources of the resource must be utilized. As an example, consider the use of wood as a fuel. As long as the production rate is within the range of the replenishable yield of the supplying forest, the production cost is constant. If demand is increased to the point that a less economic source of wood must be brought into production (e.g., lower quality, further away) then the production cost would increase.

As with depletable resources, all of the potential renewable resources need to be included in the network.

Conversion Node This node is used to simulate energy technologies that change energy from one form to another. Examples of conversion processes are boilers that convert fuel to steam, electric power plants that convert fuel to electricity, and coal cleaning plants that convert raw coal to clean coal. These nodes may represent both supply system technologies and end use demand technologies.

There are two equations used to relate the input and output quantities and prices for a conversion process. For the quantity relationship the equation is:

$$Q_o = Q_i \times \eta \quad (\text{E-2})$$

Figure E.5 Supply Curve
for Depletable Resource

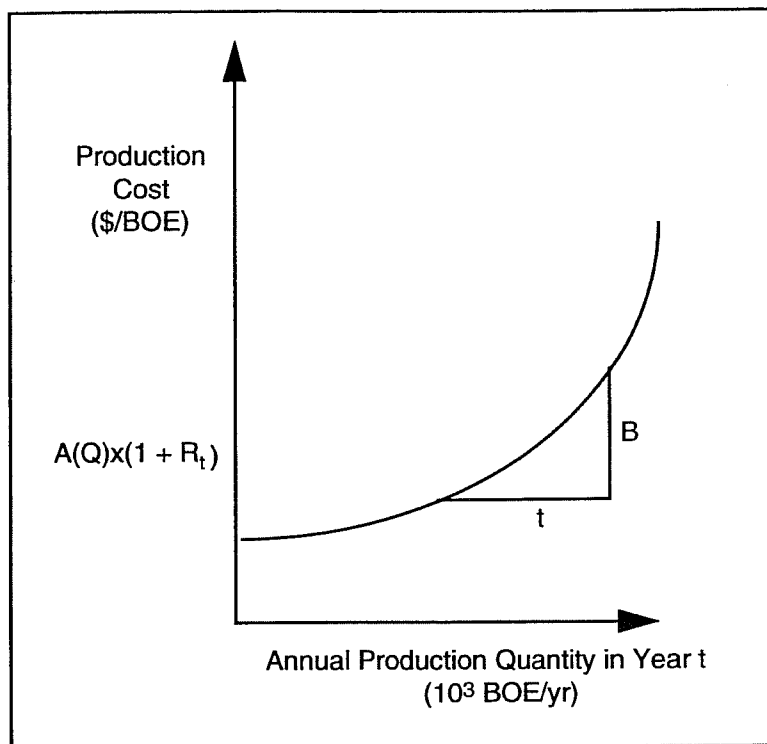
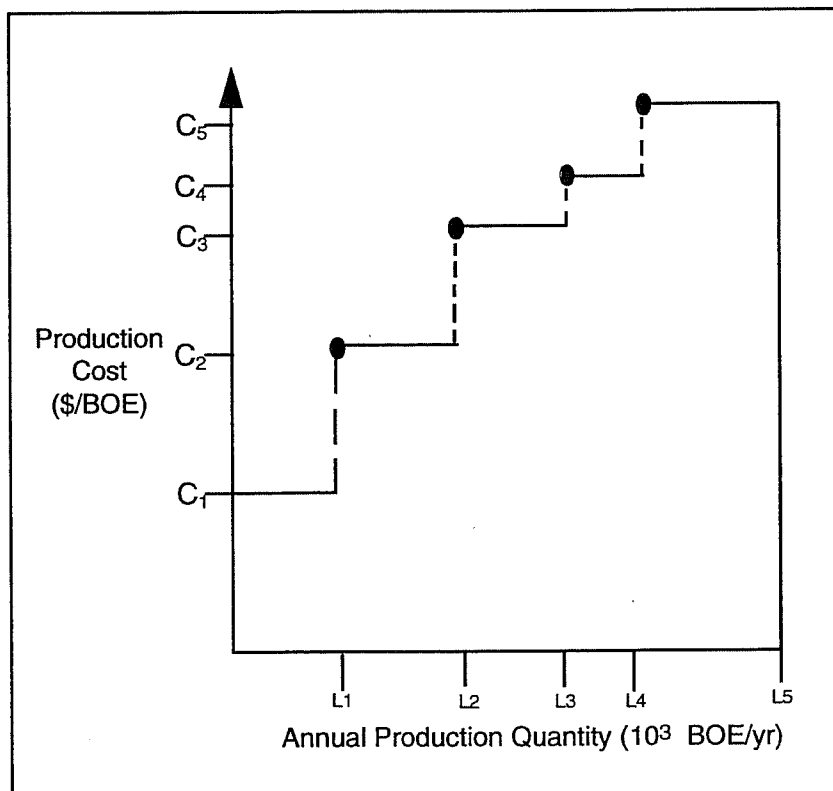


Figure E.6 Supply Curve
for Renewable Resources



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where Q_o is the output quantity, Q_i is the input quantity, and f is the thermodynamic efficiency of the process. For the price relationship the equation is developed by relating total revenue produced by the process to total cost. This is given in the following:

$$Q_o \times P_o = Q_i \times P_i + OM \times Q_o + TCI \times CRF_{i,n} \quad (E-3)$$

Revenue	Fuel Cost	Operating Cost	Amortized Capital Cost
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where P_o is the output price, P_i is the input price, OM is the operation and maintenance cost per unit of output, TCI is the total capital investment, and CRF is the capital recovery factor for a facility lifetime of n years at an interest rate of i . The output price P_o is solved from this equation since all other variables are known.

This is a straightforward way of representing a wide variety of energy technologies. Conversion nodes can be used to simulate a single facility or an aggregate of many facilities of the same type.

Multiple Output Node These nodes are similar in concept to the conversion node in that they represent technologies that convert energy from one form to another. They differ in that there is more than one energy form produced. Typical examples of a multiple output node are refineries, which produce a spectrum of petroleum products from the input crude oil, and cogeneration systems, which produce both electricity and steam.

The equations relating the input and output quantities and prices are analogous to those for the simple conversion node with the exception that there are separate efficiencies for each of the output products relative to the input (e.g., corresponding to a refinery output slate) and the price equation includes the revenue generated from all of the output products.

There are two special considerations in using this type of node. The first is that the output product mix may not always meet the demand for the individual products. Because the output mix is determined by the technology configuration (e.g., how a refinery is configured for distillation, cracking, etc.), there may be surpluses of some products and shortages of others if the configuration does not exactly match demand. This situation is handled by specifying which output product will be used to determine the input required and by using stockpile nodes to absorb any excess. The result is a reasonable simulation of actual situations.

The second consideration is the distribution of production cost among the various output products. As an example, refineries have very complex schemes for allocating costs among the various petroleum product outputs. The model allows the user to apply any chosen cost distribution scheme.

Multiple Input Node This node is also analogous to the Conversion node; however, it simulates technologies that require a mix of two input energy types to generate a single output form of energy. Examples of its use are a solar water heater with an electric backup, a blender to mix gasoline and ethanol to provide gasohol, and a preprocessor to blend heavy crude oil with lighter oil prior to refining.

In using this node in a network, the two input flows are assumed to be in fixed ratio. The resulting equations for output prices and quantities are then very similar to those for the Conversion Node.

Decision Node This node is one of the most important in defining the role that competing energy technologies will play in a future energy system. They represent the market forces at play when choices are made to use a particular type of energy. The approach used in simulating the market decision process is to assume that the market share of an energy source is inversely proportional to its price relative to its competitors. The equation used to relate input and output quantities is:

$$\sum (\mathcal{Q}_{in_j}) = \sum (\mathcal{Q}_{out_k}) \quad (\text{E-4})$$

where Q_{in_j} are the competing input energy forms, and Q_{out_k} are the outputs distributed to the demand customers. Note that in this node, there is no change in either the form or total quantity of energy.

The market share of each of the competing input energy sources is determined by the equation:

$$MS_j = \frac{\left(\frac{1}{P_j}\right)^r}{\sum_j \left[\left(\frac{1}{P_j}\right)^r\right]} \quad (\text{E-5})$$

where MS_j is the market share of input source j , P_j is the price of input source j , and r is a parameter that determines the sensitivity to prices. Figure E-7 shows how this computation affects the use of one source relative to another.

The use of a market share algorithm is one of the things that distinguishes the equilibrium approach from other energy modeling techniques. This technique allows for the simulation of market operation with multiple decision-makers. In contrast, least-cost optimization approaches, while suitable for simulating a single decision-maker, cannot address the more complex behavior of multiple decision-makers. For example, in simulating the choice of consumers for using natural gas or electricity for cooking (assuming both are readily available), the market share algorithm can simulate the condition where some consumers will prefer one to the other. If the cost of natural gas and electric cooking were the same, it is reasonable to expect that they will share the market equally. This is the result using Equation E-5. As the price of one relative to the other increases, its market share will decrease. This same result can be given by the application of Equation E-5.

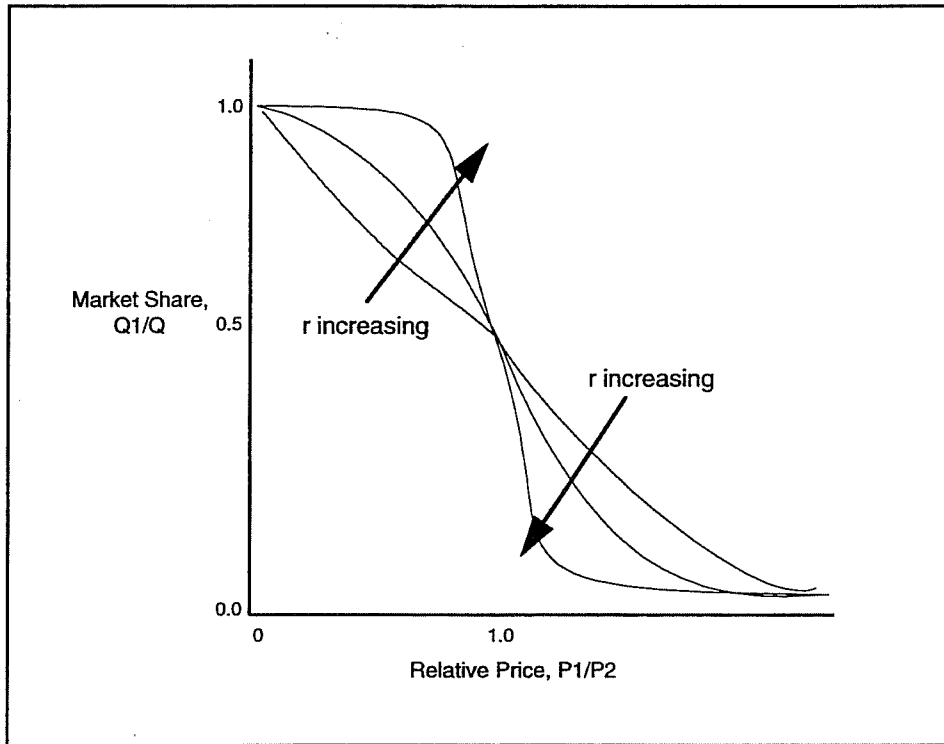


Figure E-7 Market Share Computation

In some instances, there is a great deal of sensitivity to price differences. Small changes in relative price will produce fairly large changes in market share. A refinery purchasing crude oil is an example of price sensitive markets. Consumers buying automobiles is an example of relatively price-insensitive markets as other factors influence the decision. The parameter r in Equation E-5 is used to simulate these different conditions. The value of r can be determined by looking at historical values of market shares and relative prices.

There are several other factors that are incorporated into the Decision Node. First, there is a lag function that can be employed. This is designed to simulate situations where a particular market cannot readily respond to price changes, even of relatively large magnitude. Existing capital equipment or difficulty in getting access to the cheaper fuel are examples of circumstances that prevent market response. The lag function determines what portion of the market is able to adjust to a change in prices. It is applied using the following equation:

$$MS_j(t) = \lambda \times ms_j(t) + (1 - \lambda) \times MS_j(t-1) \quad (\text{E-6})$$

where:

$MS_i(t)$ is the market share at time t with lag considerations included

$ms_i(t)$ is the market share that is computed without lag considerations (i.e., by Equation E-5)

λ is the lag parameter

The value of λ can be related to the life expectancy of the energy equipment and therefore, to its turnover rate.

Second, factors other than price determine market share. This can be handled in the model by applying price premiums to certain sources to account for their desirability based on other factors. For example, consumers will almost always choose to light their homes with electricity rather than kerosene lamps even though the delivered cost of kerosene light is lower than electric light. The level of price premiums can be estimated by looking at historical data.

Third, government policies may distort the market process by imposing requirements or restrictions on fuel choice that override market forces. A government policy to use domestically refined petroleum products rather than imported products (usually made to protect local jobs) will change the price-determined market share. The model can accommodate these policy conditions.

Overall, the Decision Node is the single most important type of node in the model in determining how the future energy system will evolve. It gives the planner a wide range of capability in simulating the behavior of various energy markets.

Pricing Node This node allows for the simulation of government and/or corporate pricing practices that affect the price of an energy form without affecting its quantity. The governing equation for quantity flow through this link is that the output quantity is equal to the input quantity. For the price, there are several forms that the relationship can take. These include:

$$P_o = a \times P_i + b \quad (\text{E-7})$$

where P_o is the output price, a is a price multiplier and b is a price increment relative to the input price P_i .

$$P_{\text{floor}} \leq P_o \leq P_{\text{ceiling}} \quad (\text{E-8})$$

where a price ceiling and/or price floor are specified

$$P_o = c \times P(L) + d \quad (\text{E-9})$$

where $P(L)$ is the price on some other link in the network.

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These relationships can be used to simulate many different types of schemes that determine the price of energy in the system.

Stockpile Node This node is a convenient way to handle overproduction of a particular energy form and its stockpiling for later use. Its use in connection with Multiple Output Nodes was already described.

Electricity Dispatching Node This node handles the special requirements for the electric sector. The manner in which electrical generation plants are used is based on the development of the load. Figure E-8 is an example of an electrical power load duration curve. It specifies the portion of time the load exceeds a given level. In dispatching generators to meet the load, electric utilities will use their lowest operating cost units (usually large hydropower, coal, or nuclear units) to meet the continuous or base load. Units with higher operating costs are brought on line as the load increases but are reduced in output or shut down as the daily load decreases. Special units (usually gas turbines, pumped storage facilities, smaller hydro units) are used to meet the peak portion of the load. These units are characterized by being able to be switched on and off rapidly but often have higher operating costs than the base load units.

Within the Electricity Dispatching Node, a load duration curve is approximated with a fifth-order polynomial. Also, the current and planned electric generation units are identified. The node proceeds to select the units to be used to satisfy the load duration curve by picking the ones with lowest operating cost first and running them as base load. Higher cost units are added later with a resulting lower overall utilization rate. The specialized peaking units are reserved to meet the peak portions of the curve. Figure E-9 shows how this would look.

The node has special features to account for units that are needed to meet an electric utility's reserve margin but are not used for generation, for units that have been planned but are not needed to meet lower demand levels, and for units that are retrofitted to change fuel.

The node will calculate the quantity of electricity generated by each of the available generators, the total cost of electricity, and the average cost of electricity generated per kilowatt-hour. The node will not determine an optimum build schedule for generation facilities. Rather, it uses the input build schedule and utilizes the available plants as needed. The build schedule can be determined by other modules in ENPEP.

Demand Node This node is at the top of the energy network and provides the demand for energy (either fuel demand or useful energy demand) that must be met by the energy system. The levels of demand can be input by selecting cases from the DEMAND module or can be entered separately. The Demand Node provides the level of demand that will be used in finding the equilibrium.

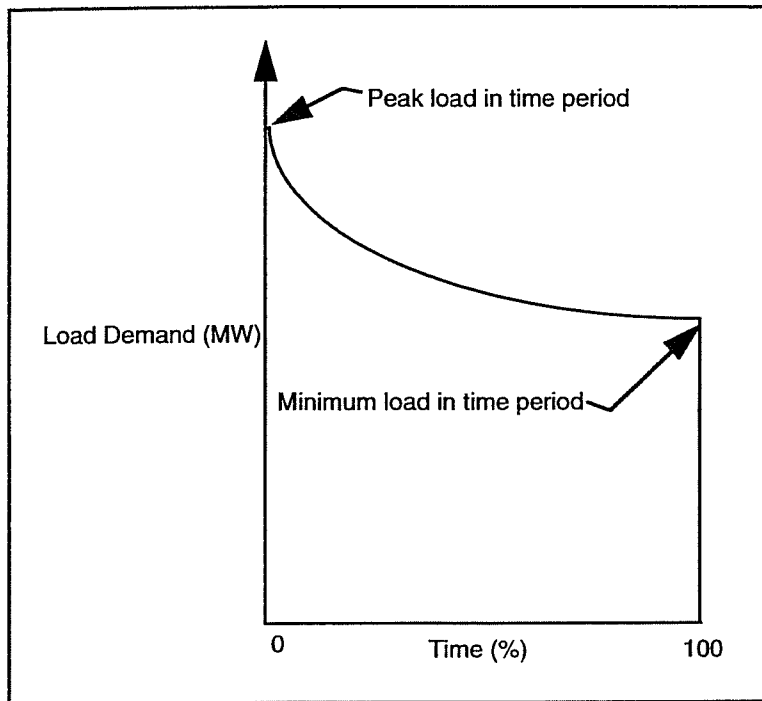


Figure E.8 Typical
Electrical Load
Duration
Curve

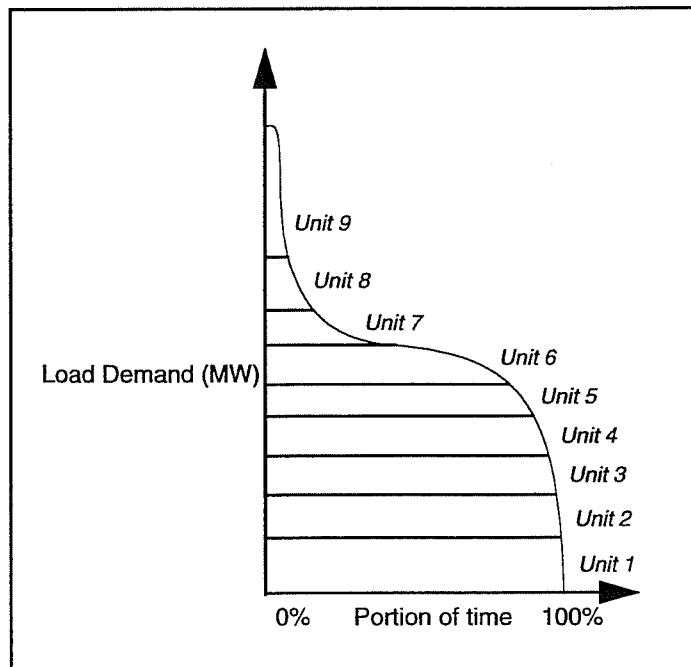


Figure E.9 Example of
Establishment of Unit
Loading Order

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As with the resource nodes (Depletable Resources and Renewable Resources), the Demand Nodes must be specified for all demands in the energy system. BALANCE will generate an equilibrium solution that satisfies all of these demands simultaneously.

Development of the Equilibrium Solution Once the energy network, consisting of the nodes and their connecting links with their associated data, has been entered into BALANCE, the equilibrium solution for all the years of interest is computed. This process starts with a base year balance. The base (first) year of the analysis is computed by starting with the base year production from all of the resource nodes (depletable and renewable) and computing quantity and price through all of the intervening nodes up to the demand nodes.

As the base year market shares at the decision nodes have been entered when the nodes were defined, this base year computation through the network simply establishes a consistent balance of quantities and prices throughout the network. Although this is a seemingly straightforward step, experience in many country applications has shown that the application of BALANCE is the first time a consistent energy balance has been drawn up for the country. A significant amount of effort is reflected in constructing this first year balance.

To compute the balance for the second year in the analysis, the equilibrium algorithm is applied. Figure E-10 illustrates how this works. The process starts with the resource nodes at the bottom of the network. A first estimate is made as to the quantity of each resource that will be produced in the year under analysis. At this point, the estimate is strictly a guess based on incrementing the previous year's production rate. The production rate is used with the resource supply curves (Figures E-5 and E-6) to determine the first guess of production cost for each resource.

An "up-pass" is then conducted in which the prices are computed across all of the nodes of the network using the resource prices as a starting point. In the up-pass, the quantities across the nodes are not calculated, only the prices. When the up-pass is completed, every link on the network has a first estimate of prices for the analysis year.

The next step is to conduct a "down-pass" in which quantities are computed across each node of the network. This calculation starts at the demand nodes at the top and proceeds downward. In the down-pass, the prices on each link are used at the decision nodes to compute market shares. These shares are passed further down as demands to the nodes below. Finally, at the bottom of the network, the total quantity of each resource that has been computed from the down-pass, is determined.

In general, the resource quantities used in the first estimate at the start of the up-pass, do not match the resource quantities computed through the down-pass. A solution algorithm is employed to readjust the quantity estimate and another up-pass and down-pass sequence is started. When the resource quantity estimate and the down-pass resource quantities are within a specified tolerance level for all resources, the solution is said to have converged to an equilibrium for that year.



Figure E.10 Illustration of BALANCE Solution Procedure

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BALANCE proceeds to step through the analysis year-by-year. The resulting solution is a set of prices and quantities on all of the links in the network for every year of the analysis period. Currently, up to 75 years may be included.

Implications of the Solution The solution that BALANCE generates provides a consistent picture of energy flow through the network for the set of assumptions and conditions that the user has specified. The solution is in "equilibrium" because the feedback effects of demand and supply adjusting to price differences have been included in the analysis.

The equilibrium solution should not be interpreted as an "optimum" solution. When looking at the entire energy system, the term "optimum" is not particularly meaningful. Each portion of the energy system (e.g., the electric sector, the oil sector, the coal sector) has a different version of optimum. Instead, the equilibrium solution represents how the energy system might develop when the conflicting demands and market forces balance each other.

The BALANCE solution is based on an analysis of annual energy flows. It is designed to give a picture of long-term trends in energy development. It is not intended to be a short-term forecasting tool. Nor is it suited to address the short-term effects of crisis or emergency conditions.

Because BALANCE does its calculations on a year-by-year basis, it is, in energy modeling jargon, "myopic". That is, it does not make current energy use decisions with the need for a projection of what will happen in the future (e.g., to energy prices). The opposite extreme in equilibrium analysis is "perfect foresight" in which the analysis in any one year depends on a prediction of what will happen throughout the future planning years. Both approaches have benefits and shortcomings. Future versions of BALANCE are planned to test a "limited foresight" approach.

Beside the basic output of prices and quantities on the links, additional data is needed to fully appreciate the results. These data are generated in the IMPACTS module of ENPEP which is discussed later.

3.5 PLANTDATA

PLANTDATA was developed to serve the needs of other ENPEP modules that need descriptions of the electric generating system as input. BALANCE, ELECTRIC and ICARUS require detailed descriptions of every electric generating unit. PLANTDATA is intended to provide a consistent set of electric generating system data, while eliminating redundant data entry. PLANTDATA has two major components:

- Thermal generating unit data
- Hydroelectric generating unit data

A summary report on all data can be printed out and used as a reference document for a particular case study.

3.6 MAED

The Model of Analysis of Energy Demand (MAED) is a simulation model designed to evaluate medium- and long-term demand for energy in a country (or region). The model was developed by the International Atomic Energy Agency (IAEA) and was originally based on work done at the University of Grenoble in France.

MAED offers an alternative approach to MACRO/DEMAND/BALANCE for estimating energy demand and electricity demand. The MAED model consists of four modules:

Module 1 (energy demand) calculates the final energy demand per energy form and per economic sector for each reference year according to the various parameters describing each socio-economic and technical development (e.g., energy efficiency) scenario.

Module 2 (hourly electric power demand) converts the total annual demand for electricity in each sector to the hourly demand, i.e., the hourly demand imposed on the grid by the respective sector.

Module 3 (load duration curve) ranks the hourly demands imposed on the grid in decreasing order of magnitude and provides the load duration curve. The curve forms a basic input to the ELECTRIC module of ENPEP.

Module 4 (load modulation coefficients) is an auxiliary module which may be used to analyze the past evolution of coefficients describing the variation of the hourly electric loads, based on load curve information determined from statistical data.

The output of the MAED model are detailed estimates of alternative energy forms used in each subsector for each year selected. The breakdown of demand by energy form and by economic sector is an important result of the analysis. The hourly electric load data can be used to produce load duration curves that serve as input to the ELECTRIC module of ENPEP.

3.7 LDC

The main function of the LDC module is to process the historical information on hourly loads of an electric power system and to create normalized load duration curves needed by the ELECTRIC and ICARUS modules. The load duration curves can be created for up to 52 periods per year, and can be projected over the years of the study period according to the given load forecast (LDC is not a load forecasting model; it is expected that the user has run BALANCE or has obtained the future load forecast by some other method). The load duration curves can be expressed either as a monotonically decreasing series of points or as a polynomial approximation. The most common polynomial approximation is with a 5-th degree polynomial.

The output of LDC is complete load input information for the ELECTRIC and ICARUS modules. Estimated load duration curves can be viewed with built-in graphics that can be rapidly accessed. Results of calculations are available in convenient tables.

3.8 ELECTRIC

The ELECTRIC module is the microcomputer version of the Wien Automatic System Planning Package (WASP), which is the well-known mainframe electric system planning model distributed by the IAEA.

The objective of the ELECTRIC module is to determine the generating system expansion plan that adequately meets demand for electric power at minimum cost while respecting user-specified constraints. ELECTRIC is directed to long-term planning beyond a 10 year time horizon and is intended to address a number of critical issues in generation planning, including generating unit size, system reliability, details of the existing system, seasonal variation in loads and hydroelectric availability, and appropriate simulation of future system operation.

A primary motivation for ENPEP's development is that evaluations of alternatives for expansion of electrical generating systems should not be conducted in isolation with respect to important related considerations, such as overall economic growth, demand for all forms of energy, supply of alternative energy forms, relative cost of energy forms, and environmental impacts of alternative supply systems. For this reason, ELECTRIC is integrated with the PLANTDATA, BALANCE, LDC, MAED, ICARUS, and IMPACTS modules of ENPEP. Although these components of ENPEP are fully integrated, the ELECTRIC module can be used as a stand-alone system. ELECTRIC comprises the following eight submodules.

LOADSY (Load System Description): Processes information describing the peak loads and load duration curves for up to 30 years. The objective of LOADSY is to prepare all the demand information needed by subsequent modules.

FIXSYS (Fixed System Description): Processes information describing the existing generating system. This includes performance and cost characteristics of all generating units in the system at the start of the study period and a list of retirements and "fixed" additions to the system. Fixed additions are power plants already committed and not subject to change.

VARSYS (Variable System Description): Processes information describing the various generating units to be considered as candidates for expanding the generating system.

CONGEN (Configuration Generator): Calculates all possible year-to-year combinations of expansion candidate additions that satisfy certain input constraints and that, in combination with the existing system, can adequately meet the electricity demand.

MERSIM (Merge and Simulate): Considers all configurations put forward by CONGEN and uses probabilistic simulation of system operation to calculate the associated production costs, ENS, and system reliability for each configuration. The module also calculates plant loading orders, if desired, and makes use of all previously simulated configurations.

DYNPRO (Dynamic Programming Optimization): Determines the optimum expansion plan as based on previously derived operating costs along with input information on capital cost, ENS cost, and economic parameters and reliability criteria.

REMERSIM (Re-MERSIM): Simulates the configurations contained in the optimized solution. By providing a detailed output of the simulation, REMERSIM allows the user to analyze particular components of the production-cost calculation, such as unit-by-unit capacity factors for each season and hydroelectric condition.

REPROBAT (Report Writer of WASP in a Batched Environment): Writes a report summarizing the total or partial results for the optimum or near-optimum power system expansion plan and fixed expansion schedules.

3.9 ICARUS

The module for Investigating Costs and Reliability in Utility Systems (ICARUS) of the ENPEP system can be used by the energy planner to analyze the detailed unit level operation of the electric generating system. ICARUS is a production-cost model with an efficient probabilistic simulation algorithm that calculates production costs and capacity factors for up to 600 unique plants and system-wide reliability for time periods of one week to one year. In addition, ICARUS is capable of simulating firm purchases and sales, emergency interties, and one energy-limited unit. In carrying out its analysis, ICARUS performs four major functions:

- Calculates the system loading order
- Calculates a system maintenance schedule
- Calculates expected energy generation and costs
- Calculates system reliability parameters

ICARUS data requirements fall into three major categories: load data, unit data and economic data. The data inputs can be retrieved from an existing *ELECTRIC* analysis or manually entered into the ENPEP system.

3.10 IMPACTS

Once an energy system configuration has been designed, the environmental impacts and resource requirements of that configuration must be evaluated. Frequently, an energy system that is designed solely from the energy supply perspective cannot be implemented because of environmental constraints or resource limitations. The IMPACTS module is designed to estimate these effects.

The approach used in the ENPEP system is to develop an energy system configuration from technical and economic considerations, then to determine the impacts. An iteration on the configuration may be necessary if the impacts prove to be unacceptable. Some modeling approaches attempt to do the technical, economic, and impact analyses simultaneously so as to arrive at the "best" energy system. A typical approach is to develop an objective function that incorporates all of these factors. In practice, the solution generated in this manner is frequently not implementable. The objective function, for example, may allow for tradeoffs between environmental quality and system performance whereas the real situation may not. Experience has shown that the iterative design process used in ENPEP is closer to actual conditions.

Facilities from both energy supply systems and energy consuming systems can be included in the IMPACTS analysis. For example, coal mines, power plants, refineries, and natural gas lines may be included as supply systems. Industrial boilers, residential space heaters, and automobiles may be included as demand facilities. IMPACTS will determine the impacts of all these types of facilities.

IMPACTS carries out five major functions:

- Develops facility build schedule
- Assigns facilities to geographical regions
- Selects impact coefficients from databases
- Applies regulatory controls
- Computes impacts

3.11 Computer Architecture

In order for a model (or set of models) to be a useful planning tool, it must also be usable. ENPEP was created to provide a state-of-the-art energy analysis capability. Along with the technical models, ENPEP provides a menu-driven user interface, automated file handling and program execution, reports in tabular and graphical form, data compression and backup facilities, a demonstration case with default data, help screens and on-line abstracts, and a detailed ENPEP User's Manual.

ENPEP was developed for use on an IBM or IBM-compatible microcomputer. IBM-compatible equipment was chosen because it is the most widely used and supported PC on a worldwide basis, particularly in developing countries. ENPEP is continually updated to take full advantage of the latest advances in computer software and hardware.

4. EXPERIENCE WITH ENPEP

ENPEP was designed for distribution to countries with a need for energy planning analysis tools. Distribution of the package is handled by the U.S. Department of Energy. Under an agreement with the International Atomic Energy Agency, ENPEP is also distributed to member countries of the IAEA as part of technical cooperation projects. There is no charge for ENPEP.

To date, all or part of ENPEP has been distributed for use in more than 30 countries. For some, the ELECTRIC module and the associated electric system planning modules are of primary interest. For others, the overall energy system analysis of BALANCE is of primary importance.

The IAEA, in cooperation with DOE, has conducted several training courses on the use of ENPEP. Participants, in teams of two or three from a country, spend up to nine weeks going through the use of the various modules. Additional courses are continually planned.

In addition to use outside the U.S., the ENPEP system is currently being used for several energy policy studies in the U.S. Studies at both the national and regional level are in progress or being planned.

One of the intents in the development of ENPEP was to maintain a continuing update of the model. A number of enhancements are in process and more are planned. Capabilities are being added to several of the modules. Graphical interfaces and output displays are being developed. Testing is an on-going process. It is intended that ENPEP evolve as the state-of-the-art in energy modeling evolves.

ENPEP SIMPLE CASE

CURRENT LIGHTING VERSUS HIGH-EFFICIENT LIGHTING

The previous sections presented the ENPEP approach and computational algorithms that the program uses to arrive at its non-linear equilibrium solution. This section shows a simple application of the BALANCE module of ENPEP. The case study that is run in this application is a simplistic representation of an energy network consisting of an energy supply sector, a transmission and distribution (T&D) sector, and an energy demand sector (see Figure 1). The energy demand sector shows two types of demands, i.e. an industrial electricity demand and a residential lighting demand. The following discussion will concentrate on the residential lighting demand. As displayed in the network, the lighting demand can either be met by conventional, incandescent lighting or by advanced, high-efficient, compact-fluorescent lighting.

This simple case will illustrate how ENPEP determines the market penetration of competing technologies (conventional vs. high-efficient), and how it can be used to model the role that high-efficient technologies, such as compact fluorescent lighting, can play as greenhouse gas mitigation options. This demonstration will also show how ENPEP models market interventions like subsidies for more efficient, yet more expensive technologies to stimulate their penetration.

The first step in the analysis is to develop the energy network with all the nodes and connecting links and to input the network and the associated data into ENPEP (see Figure 1). This means, the user defines certain technical and economic characteristics for the conversion process nodes in the network, and enters base year market shares at each of the decision nodes. Some of the assumptions used in this case are given in the table below.

ASSUMPTIONS FOR SIMPLE ENPEP CASE

Variable	Assumption	Remarks
Capital cost incandescent	\$0.75	
Life expectancy incandescent (ic)	750 h = 0.86 years	@10% capacity factor
Current penetration compact fluorescent (co-fl)	3%	
Capital cost compact fluorescent	\$18-19	In retail stores
Life expectancy compact fluorescent	10,000 h = 11.4 years	11.4/0.86 = 13/1 (only integers allowed in ENPEP)
Efficiency compact fluorescent	4.2 x efficiency of ic	18 W compact fluorescent equals 75 W incandescent
Residential cost of electricity	10¢ per kWh	
Subsidies	30%, 62%	Commonwealth Edison sells co-fl for \$12.5 to its customers Some utilities sell co-fl for as low as \$5-7 to their customers
Resource information	\$5.5/BOE import \$5.9/BOE domestic	Import: price 2% growth/yr. Base year 5,000 kBOE Domestic: price 4% growth/yr. Base year 10,000 kBOE
Growth rate residential lighting demand	between 1% and 3%	3% (1993-1997), 2% (-2002), 1.5% (-2007), 1% (-2012)
CO ₂ emission factor	94.3 kg CO ₂ /GJ	

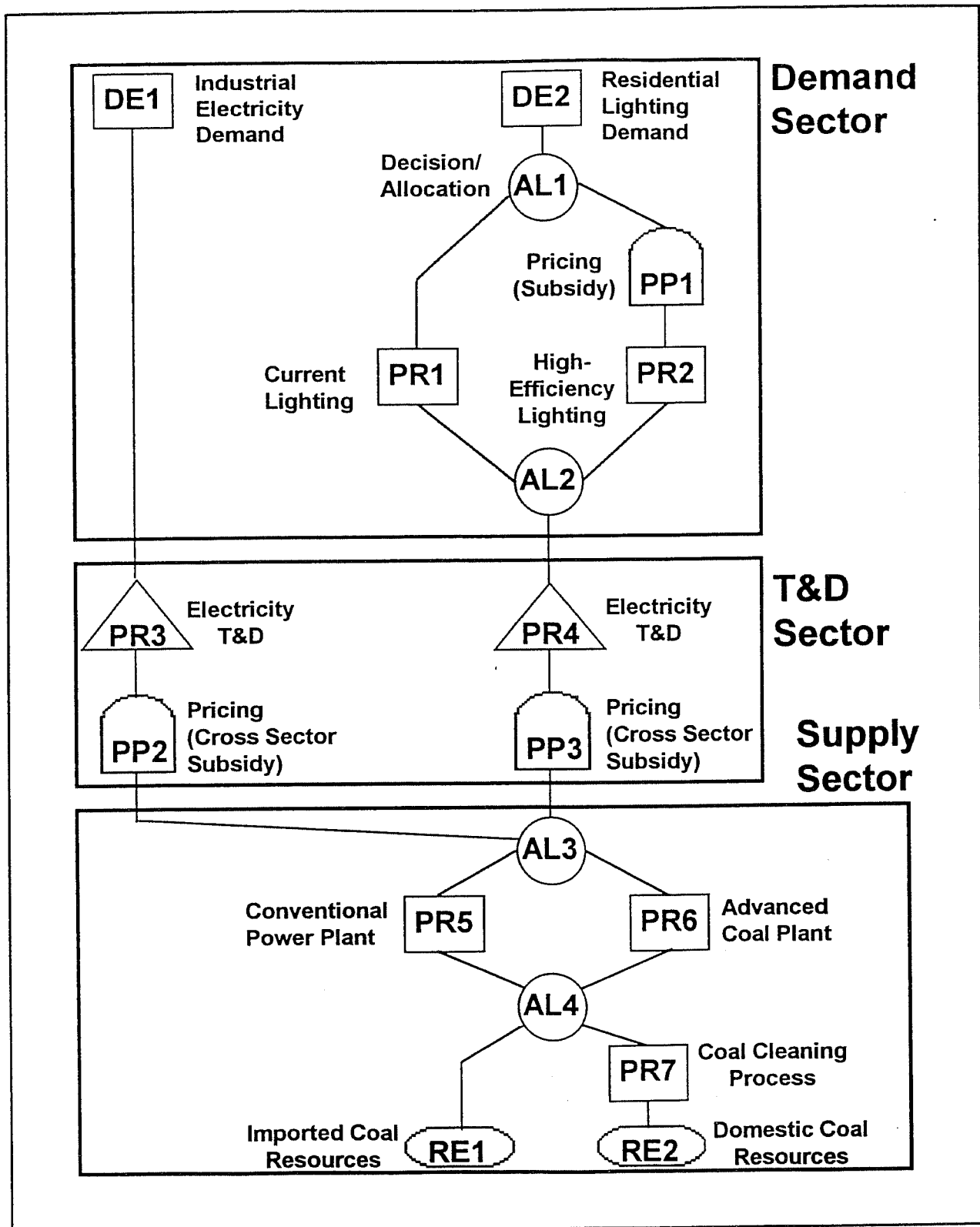


Figure 1: ENPEP Simple Case Network

BALANCE first calculates the base year quantities and prices on all links of the network. This is done to check the consistency of the input data. When the model computes the balance for the subsequent years, it starts out with estimating the production rates for all resources at the bottom of the network. Based on these resource production rates, the program moves up the network (up-pass) to the demand nodes and determines the prices on each link. Once at the top, BALANCE reverses and works its way down through the network (down-pass) computing the quantities on each link. The down-pass starts with previous year's demand incremented by this year's demand growth rate. When the model reaches the bottom of the network, it compares the computed resource demand with the estimate it used for the up-pass. The estimate is adjusted, and the process is repeated until the up-pass estimate and the down-pass quantity are within a specified range. Is this the case, the model is said to have converged to an equilibrium in this year.

Case without Subsidies for Compact Fluorescent Lighting

In the base year, BALANCE starts out with a given amount of resource utilization, i.e. 5,000 kBOE imported coal and 10,000 kBOE domestic coal. The domestic coal is cleaned prior to combustion (the clean domestic coal is assumed to have the same combustion characteristics as the imported coal). In the base year, the majority of the coal is burned in the conventional coal-fired power plant (85%). Only 20% of the electricity generated is allocated to the residential sector. After adding cross-sectorial subsidies (industrial - residential) and transmission and distribution costs, 928 kBOE are delivered to the residential sector at a cost of 10¢/kWh. For the base year, a 4% market share is assumed for compact fluorescent lighting. Taking into account conversion efficiencies, this translates into 220.4 kBOE of lighting demand delivered by incandescent and 9.3 kBOE by compact fluorescent lights (total lighting demand of 229.7 kBOE).

In subsequent years, the total lighting demand increases by the demand growth rates specified by the user. The model allocates this lighting demand to incandescent and compact fluorescent lights. BALANCE determines the penetration rates for both technologies according to the relative prices of the alternatives. In this case, the levelized cost of incandescent lights are about 61-63% that of compact fluorescent lights. The pricing node that will be used to model subsidies is inactivated at this time.

Assuming a relatively low price sensitivity and a long lag time in terms of consumer response (sensitivity of 3.0, lag parameter of 0.15), the market share of high-efficient lighting slowly increases to about 19% at the end of the year 2012 as displayed in Figure 2. This increase may be attributed to more intense promotion of high-efficient technologies and a growing consumer awareness. However, this rise in the compact fluorescent market share may be too little to make a significant contribution to greenhouse gas mitigation. Interventionist measures (subsidies) may have to be employed to ultimately achieve a much larger penetration of this advanced technology (see below).

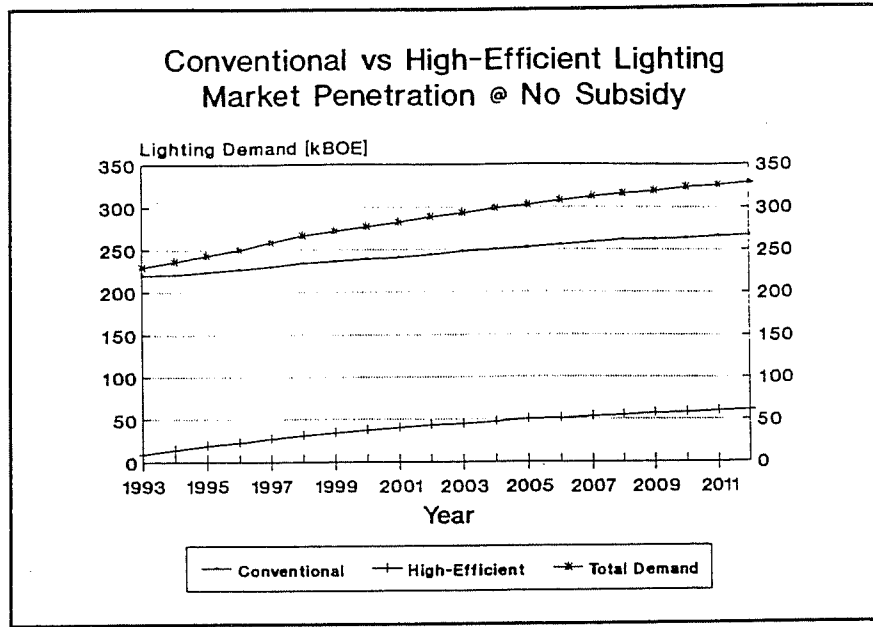


Figure 2: Market Penetration

Further down in the network, the model determines how the electricity demanded by the residential (and industrial) sector is generated. The decision to use an advanced vs a conventional power plant, again, is made based on relative prices of the generation alternatives. As the advanced coal plant is cheaper (levelized cost is about 93% of conventional plant cost), its market share increases over time from about 17% to about 69% (Figure 3). This degree of change can be attributed to the medium-to-high price sensitivity of 11.0. However, annual changes are slow but steady as the power sector usually operates with a significant lag time (lag parameter 0.2).

The decision what type of coal to use for combustion in the power plants is made one step down. The model would prefer the cheaper import coal in the years subsequent to the base year. However, an import restriction (either physical or legal) imposes a limit of 9,500 kBOE per year on the use of import coal. Once the import limit is hit, the import coal production remains constant. Later increases in coal demand have to be met by the more expensive domestic coal (see Figure 4).

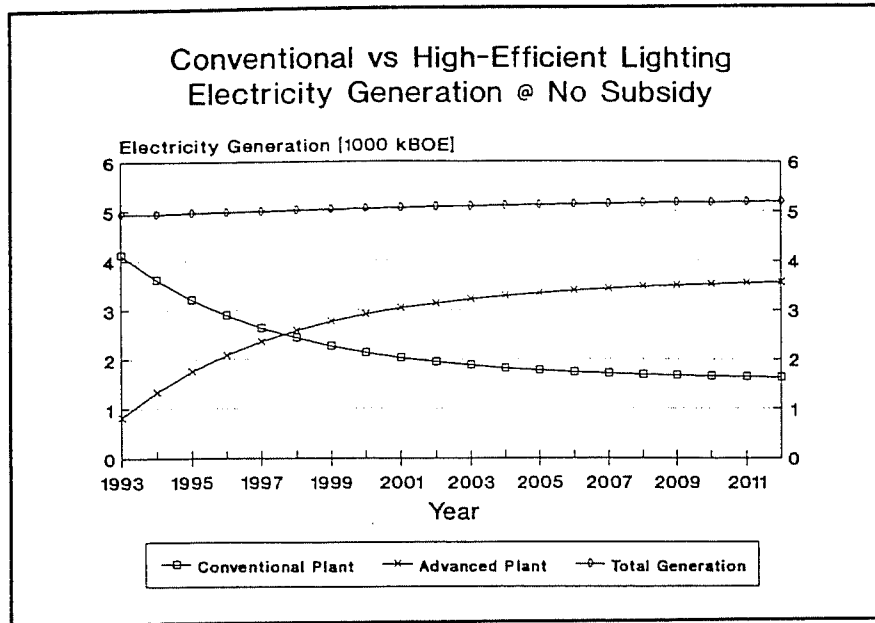


Figure 3: Electricity Generation

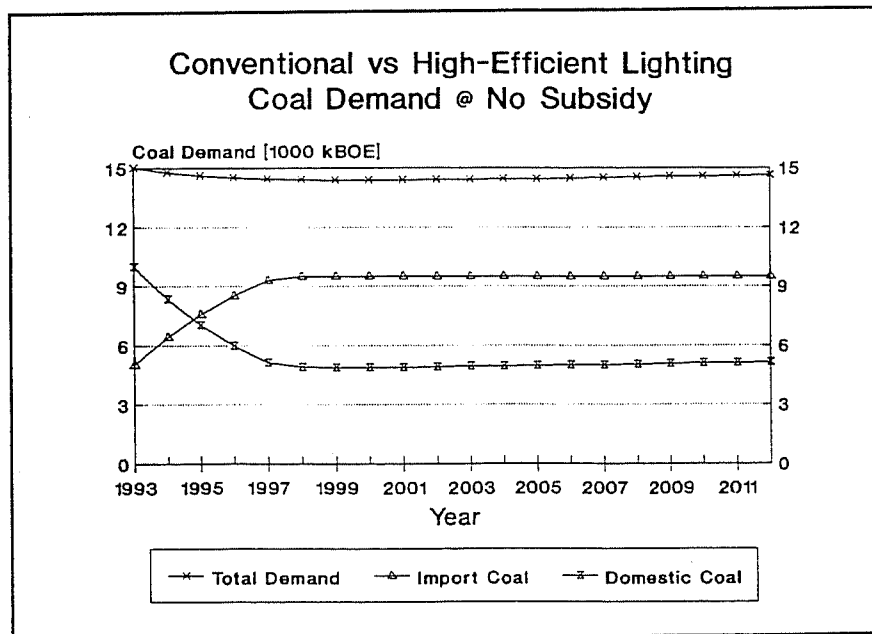


Figure 4: Coal Demand

Case with Subsidies for Compact Fluorescent Lighting

Subsidies are used to stimulate market penetration of certain technologies. In this case, a subsidy will be put in place to raise the market share of the high efficient compact fluorescent lighting. In BALANCE, subsidies are modeled with pricing nodes. As shown in Figure 1, a pricing node is included in the network between allocation node AL1 and conversion process node PR2. This pricing node allows to reflect subsidies on the capital cost of the high-efficient lighting technology.

Subsidy levels compare to special promotions of compact fluorescent light bulbs by electric utilities in form of Efficiency Kits and the like. The average retail price for high-efficient light bulbs is taken to be \$18.5. The first subsidy level of 30% compares to the price per light bulb in the Efficiency Kit of an Illinois utility (approx. \$12.5 per light bulb). The second level of 62% subsidy translates into a reduction of capital costs to about \$7 per bulb. Some utilities offer prices as low as \$5-7 per light bulb.

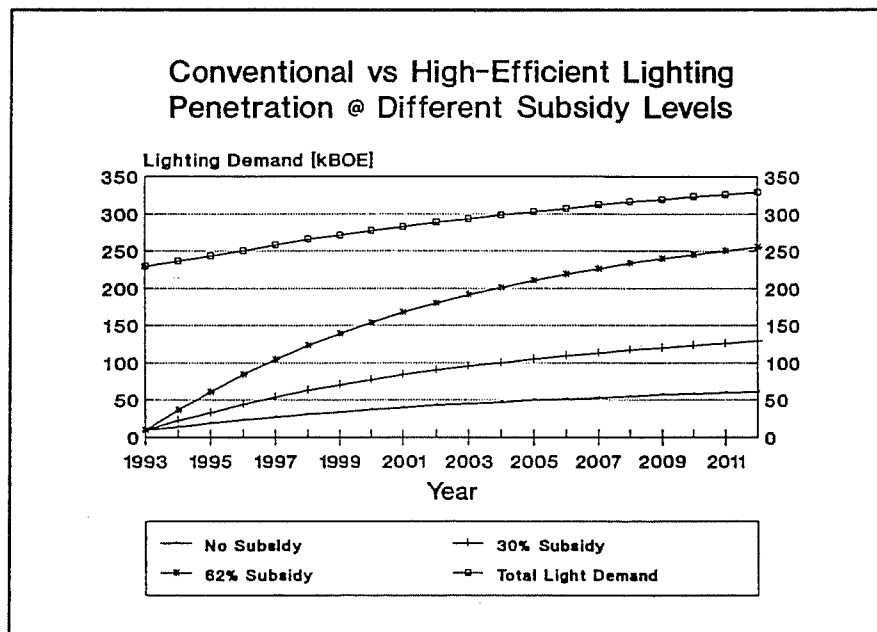


Figure 5: Market Penetration for Different Subsidy Levels

When the pricing node in the residential lighting sector is activated, the price of the high-efficient lighting is multiplied in the up-pass by a factor of 0.7 and 0.38, respectively. When BALANCE determines the market shares of both lighting technologies in the down-pass, the model compares the actual price of the current lighting with the modified price of the compact fluorescent lighting. A subsidy of 30% reduces the price difference of the two technologies (levelized cost of incandescent lights are about 87-90% that of compact fluorescent lights). The

market share of the high-efficient light goes up to 39% by the year 2012. The levelized cost of incandescent lighting rises to about 161-165% that of compact fluorescent lights when the subsidy is raised to 62%. Figure 5 shows the market shares over time for different subsidy levels.

Figure 6 displays the impact on electricity generation of varying subsidy levels. With a 62% subsidy, the rising market penetration of the high-efficient lighting more than offsets the growth in lighting demand. The electricity demand falls off. The effect on CO₂ emissions is given in Figure 7. It becomes apparent that a fairly high subsidy is needed to have a significant impact on CO₂ emissions.

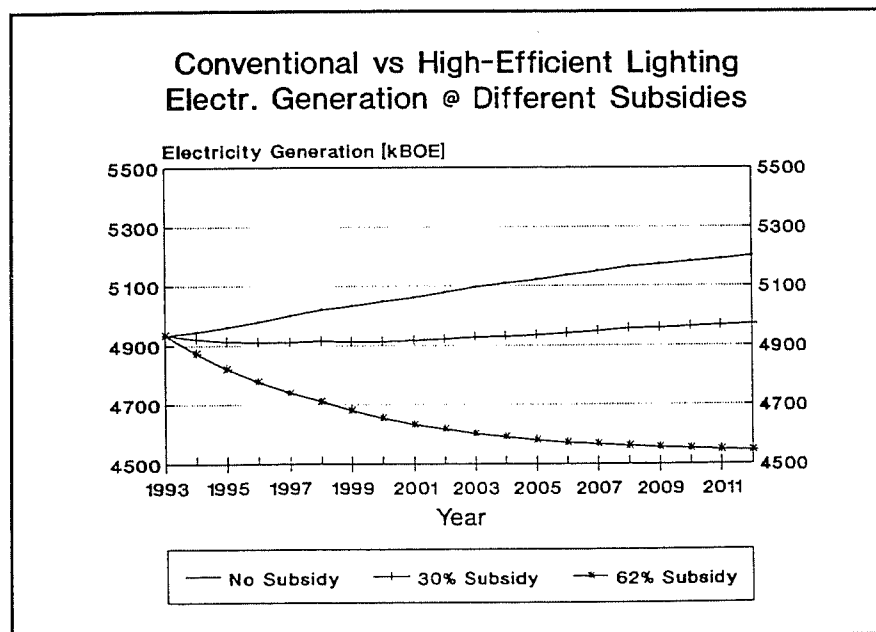


Figure 6: Electricity Generation for Different Subsidy Levels

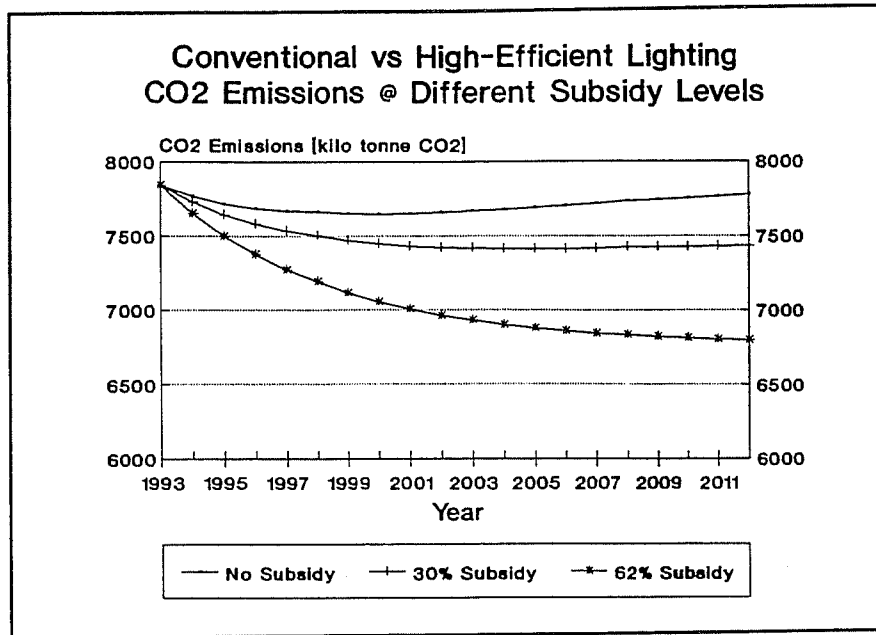


Figure 7: CO₂ Emissions for Different Subsidy Levels